Sci. Annals. Fac. Phys. & Mathem., Univ. Thessaloniki, 20b, 37 (1980)

ELECTRICAL INVESTIGATIONS ON HEAVILY DOPED SEMICONDUCTORS: THEORY VERSUS EXPERIMENT

By

I. Y. YANCHEV AND B. G. ARNAUDOV

Semiconductor Physics and Technology, Research Laboratory, University of Sofia

Abstract. *The random potential due to fluctuations in the charged impurity concentration in the case of heavy doping modulates the energy band of the semiconductor. Theoretical results concerning the statistical characteristics of this random potential as well as the form of the density of states function are given, at low and strong compensation.*

At strong compensation and low enough temperatures the amplitude of the potential is large and the electrons are localised in the deepest fluctuations of the potential relief. Then the conductivity is effected by means of thermal activation to the mobility edge or by hopping between localised states. Several hopping conductivity dependences of the form $\sigma \sim exp(-T^p)$ *where p can take the values 1, 5/11, 1/4 or 1/2 have been predicted theoretically and observed experimentally in GaAs, CdTe, Ge etc.*

Taking into account the correlation in the impurity distribution enables to reach a reasonable accordance between theoretical and experimental values of the main parameters of the activation and hopping conductivity in GaAs LPE layers.

The electron scattering due to the random impurity potential in degenerated GaAs and InAs is considered briefly as well.

1. INTRODUCTION

Most semiconductor devices use heavily doped material in which the impurity concentration is high enough so that the electrons they provide into the conduction band form a degenerated Fermi gas even at room temperature. (Here n-type material will be considered for concreteness). For this to be the case the interimpurity distance $N_D^{-1/3}$ should be smaller than the effective Bohr radius a_B, i.e. $N_D a_B^3 >> 1$. In this case the simple picture of individual impurity states is inade-

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

quate to describe the relevant properties of the semiconductor. Actually, at concentrations $N_D \geq 0{,}02a_B^{-3}$ Mott's transition takes place and there are no bound states on single impurity centres. Instead, a tail of localised states joined to the parent band appears. It is due to the clustering of several impurities which create sufficiently deep potential wells capable to bind electrons. The random potential dne to the fluctuations in the impurity concentration leads also to some specific

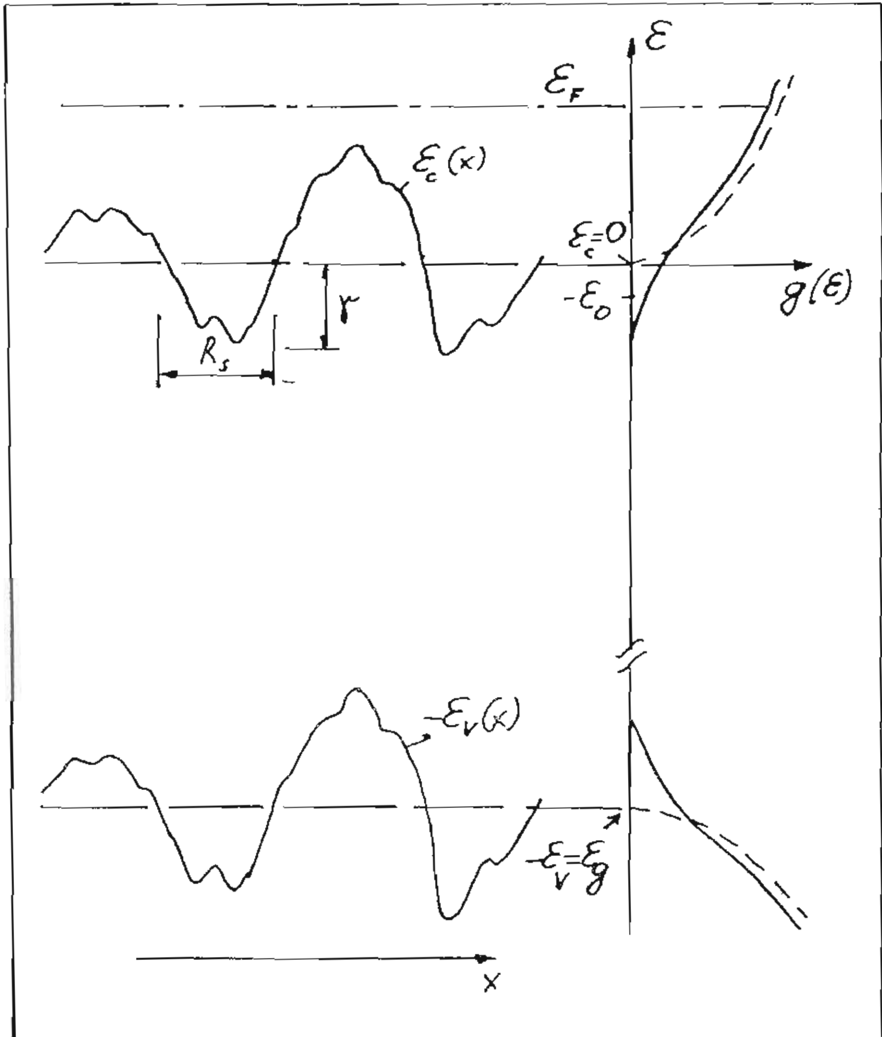

Fig. 1

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

scattering of the electrons with energies near the Fermi level. The qualitative diagram of a heavily doped semiconductor is shown in Fig. 1.

Using a number of pioneering papers as a framework, we will describe the statistical characteristics of the fluctuating potential and the density of states in heavily doped semiconductors, first in the case of low compensation. Our aim is to make clear the basic assumptions, simplifying approximations and range of validity of various theories. The fine details can be obtained from a number of review articles and monographs [1 to 4].

Then we will discuss the effect of the scattering by the random impurity potential.

Another main topic is the description of the electron states and conductivity mechanisms in heavily doped strongly compensated semiconductors. A comparison between theoretically predicted and experimentally observed temperature dependences of conductivity in GaAs, Ge and CdTe will he given.

2. IMPURITY POTENTIAL AND ELECTRONIC DENSITY OF STATES AT LOW COMPENSATION

It is well-known from the experiment that the electrons at the Fermi level in heavily doped semiconductors are nearly free. In fact, their mean kinetic energy is of the order of the Fermi energy $E_F^{(0)} = \hbar(3\pi n)^{2/3} / 2m$ where n is the electron concentration, m the effective mass. Their potential energy is of the order $q^2 N_D^{1/3} / 4\pi\varepsilon\varepsilon_0 E$ where N_D is the donor concentration, ε - the static dielectric constant. The condition for heavy doping $N_D a_B^3 \gg 1$ means that this potential energy is small compared to the kinetic energy.

In order to describe the distribution of the random impnrity potential we have to take into account the electron screening. The usual situation in heavily doped semiconductors is such that this potential is smoothly varying over the electron wavelength, so that it can be obtained by using the semiclassical Thomas-Fermi type equation. The condition that the mean potential energy is much smaller than the mean kinetic energy enables one to linearize this equation. Then we

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

get the usual result that the impurity density fluctuations are screened independently of each other at a distance

$$R_s = \frac{\alpha_B}{2}\left(\frac{\pi}{3}\right)^{-1/6}(n\alpha_B^3)^{-1/6}$$

which is the well-known Thomas-Fermi screening radius.

It is clear that R_s is larger than the interimpurity distance $N_D^{-1/3}$, so that the typical fluctuations contain a large number of impurities. Thus, the potential energy of the electron iu such a random field should obey Gaussian statistics and can be characterized by the pair correlation function

$$\langle V(\tau)V(\tau')\rangle = \frac{\gamma^2(R_s)}{2}\, e^{-|\tau - \tau'|/R_s} \tag{2}$$

where brackets denote averaging over impurity positions.
The mean squared value of the potential energy $\gamma(R_s)$ is another typical characteristics of the heavily doped semiconductor:

$$\gamma(R_s) = \frac{q^2}{\varepsilon\varepsilon_0 R_s}(N_D R_s^3)^{1/2} \tag{3}$$

According to the previous consideration, the distribution function of the potential energy is Gaussian:

$$F(V) = \frac{1}{\sqrt{\pi}\gamma}\exp(-V^2/\gamma^2) \tag{4}$$

It is now straightforward to obtain the semiclassical result of Kane [5] for the density of electronic states in such a potential:

$$g(E) = \frac{(2m)^{3/2}}{2\pi^2\hbar^3}\int_{-\infty}^{E}\sqrt{E-V}\,F(V)dV \tag{5}$$

This function has been tabulated in [5, 6]. Its asymptotic behaviour is as follows. At large positive euergies ($E > 0$, $E \gg \gamma$) it is close to the unperturbed band deusity of states $g_0(E) = \frac{(2m)^{3/2}\sqrt{\gamma}}{2\pi^2\hbar^3}$

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

$$g(E) = g_0 - \frac{(2m)^{3/2}\gamma^2}{32\pi^2\hbar^3 E^{3/2}} = g_0 \left(1 - \frac{\gamma^2}{16E^2}\right) \qquad (6)$$

For large negative energies, ($E < 0$, $|E| >> \gamma$) it falls down according to

$$g(E) = \frac{m^{3/2}\ \gamma^{1/2}}{4\pi^2\hbar^3} \left(\frac{\gamma}{E}\right)^{3/2} \exp(-E^2/\gamma^2) \qquad (7)$$

This reflects the Gaussian statistics of the potential in the low-energy states which form a band tail.

The discussion has so far dealt with the conduction band but the valence band is also affected by tbe potential due to the donors. The analysis is essentially the same as for the conduction band. The random potential for holes is of opposite sign to the electrons potential but because of the symmetry of F(V) the expression for the valence band density of states is identical to eq. (6), except that the hole effective mass must be used.

The semiclassical approximation is a fundamental limitation on the validity of the theory. It does not take account of the kinetic energy of localization. The latter should be included in the theory for the deep states which have a relatively large kinetic energy due to localization in a small volume of negative potential. Because the semiclassical theory neglects kinetic energy effect, it places states at energies, which are too low and tends to overestimate the tail length.

Nevertheless, this method still remains one of the simplest to apply and it provides a tolerably accurate single function expression for g(E) throughout the band.

The full quantum mechanical description of the low-energy tail states has been given by Halperin and Lax [7]. They have used a variational method with a trial wavefunction $f(\bar{\tau} - \bar{\tau}_0)$ the shape of wbich is determined by the optimum size of the fluctuation which can produce a bound electron state. The latter has an energy

$$E(\bar{\tau}_0) = \int f(\bar{\tau} - \bar{\tau}_0) \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\bar{\tau})\right] f(\bar{\tau} - \bar{\tau}_0) d^3\bar{\tau} \qquad (8)$$

The $\bar{\tau}_0$ dependence of $E(\bar{\tau}_0)$ is contained in the potential energy part

$$V_B(\bar{\tau}_0) = \int f^2(\bar{\tau} - \bar{\tau}_0) V(\bar{\tau}) d^3\bar{\tau} \qquad (9)$$

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

$V_s(\overline{r}_0)$ fluctuates about a zero mean value as $\overline{r}_0$ varies. Halperin and Lax assume that a bound electron state can be associated with each local minimum of the smoothed potential $V_s(\overline{r}_0)$. The variational calculation gives an eigenstate $E(\overline{r}_0)$ which overestimates the true energy so that the calculated density of states will be smaller than the true one. By maximizing it with respect to the electron wavelength, one can find an approximation for g(E). The result of Halperin and Lax is

$$g(E) = \frac{\alpha(\nu)}{E_s \zeta^2 R_s^3} \exp\{-\beta(\nu) \mid 2\zeta\} \tag{10}$$

Here $\alpha(\nu)$ and $\beta(\nu)$ are dimensionless functions of the reduced energy $\nu = E / E_s$, $E_s = \hbar^2 / 2mR_s^2$ is the kinetic energy of localization, $\zeta = \gamma^2 / 2E_s^2$. The plot of $\alpha(\nu)$ and $\beta(\nu)$ is shown in Fig. 2 and Fig. 3.

Two asymptotic cases should be considered. In the case when $\zeta \gg 1$, which is referred to as classical, the typical potential well of size R_s and depth γ (R_s) contains many electron states. Then large energies $(\nu \gg 1)$ are essential in eq. (10). The asymptotic expression for $\beta(\nu)$ is

$$\beta(\nu) \sim \nu^2 \tag{11}$$

and the density of states is Gaussian.

In the opposite "quantum" case $(\zeta \ll 1)$, the typical potential well of size R_s does not contain bound states. In this case the electrons are localized in potential wells of typical size equal to the electron wavelength $l = \hbar / \sqrt{2mE}$ which is larger than the screening radius. Then the asymptotic form of the expression is

$$\beta(\nu) \sim 3\sqrt{\nu} \tag{12}$$

Thus, in the intermediate case the density of states varies as

$$g(E) \sim \exp(-|E|^s), \qquad 0{,}5 \leq s \leq 2 \tag{13}$$

The method of Halperin and Lax is restricted to the energy states deep in the tail, where Gaussian statistics of the potential can be assumed. It may be applied to semiconductors with random impurity distribution. This is plauzible for uncompensated material provided the linear screening theory is valid. However, if the semiconductor has been doped during the growth process or has been subject to ther-

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

mal treatment, the distribution of the impurities in it is not random. It is determined by the distribution of the ionized impurities and free carriers in the plasma which existed at some high temperature T_0 at which the impurity diffusion has been frozen out. The statistical properties of the random potential have been studied in this case by Galpern and Efros [8]. They have shown that the correlation function of the potential $\langle V(\tau)V(\tau')\rangle$ has Fourier transform

$$D(k) = \frac{2N_D q^4 (k^2 + R_s^{-2})}{\varepsilon^2 \varepsilon_0^2 k^4 (k^2 + R_s^{-2} + R_0^{-2})} \tag{14}$$

Here R_s is the electron screening radius and

$$R_0 = (\varepsilon \varepsilon_0 k_B T_0 \,/\, N_D q^2)^{1/2} \tag{15}$$

is the Debye length due to the ionic screening at the temperature T_0. This correlation function takes into account the mutual repulsion between ionised donors which had determined their position prior the solidification of the crystal. The Coulomb correlation in the impurity distribution is important provided $R_0 < R_s$. Then the typical size of the potential fluctuations is of order R_0 and their amplitude is given by the rms value

$$\gamma(R_0) = \frac{q^2}{\varepsilon \varepsilon_0 R_0} (N_D R_0^3)^{1/2} \tag{16}$$

In this case the density of states in the tail has been calculated by Koynov and Yanchev [9] which have used the method of Halperin and Lax. The density of states is given by equation (10) with a different functions $\alpha(\nu)$ and $\beta(\nu)$ and R_0 instead of R_s.

The asymptotic behaviour in the classical case is as follows

$$\alpha(\nu) \sim 10^{-3} \nu^{7/2} \; ; \qquad \beta(\nu) \sim \nu^2 \tag{17}$$

so that the density of states falls off as a Gaussian with a different characteristic energy. In the quantum case the asymptotic behaviour of g(E) is completely different:

$$g(E) = 10^{-2} \frac{E^{7/2}}{\zeta^2 E_k^{9/2} R_0^3} \exp\left(-\frac{5}{8} E^{3/2} \,/\, E_B^{1/2} k_B T_0\right) \tag{18}$$

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

where $E_k = \hbar^2 / 2mR_0^2$ and $E_B = mq^4 / 2\varepsilon^2\varepsilon_0^2\hbar^2$ is the effective Bohr energy.

The restrictions on these results are those for the validity of Gaus-

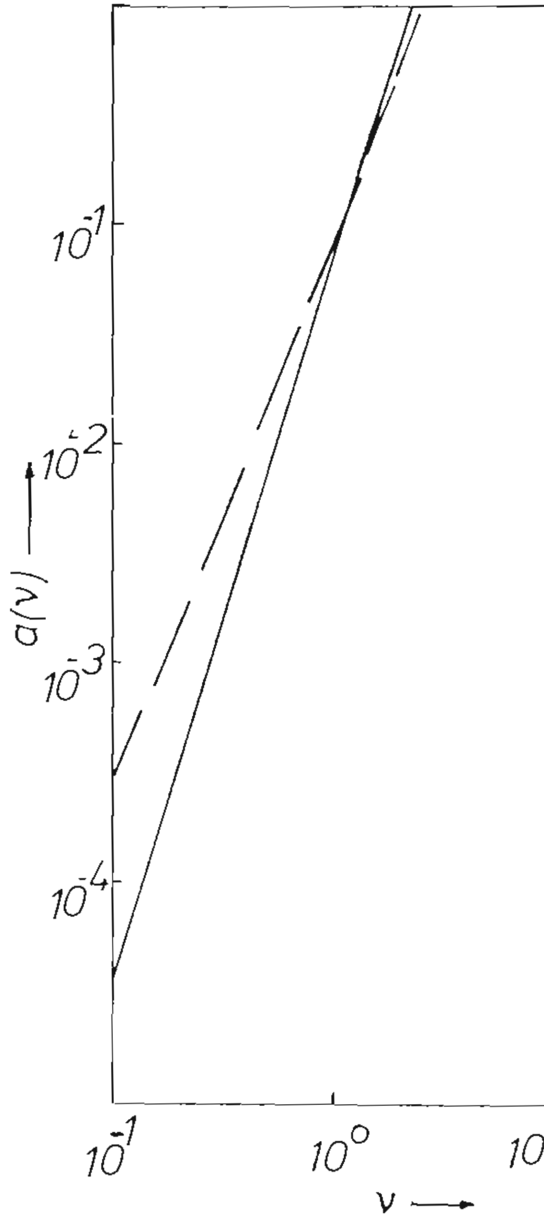

Fig. 2

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

the

y of Gaus-

sian statistics. Namely the typical well with a size either R_0 (in classical case) or $l = \hbar / \sqrt{2mE}$ (in the quantum case) should con a large number of impurities:

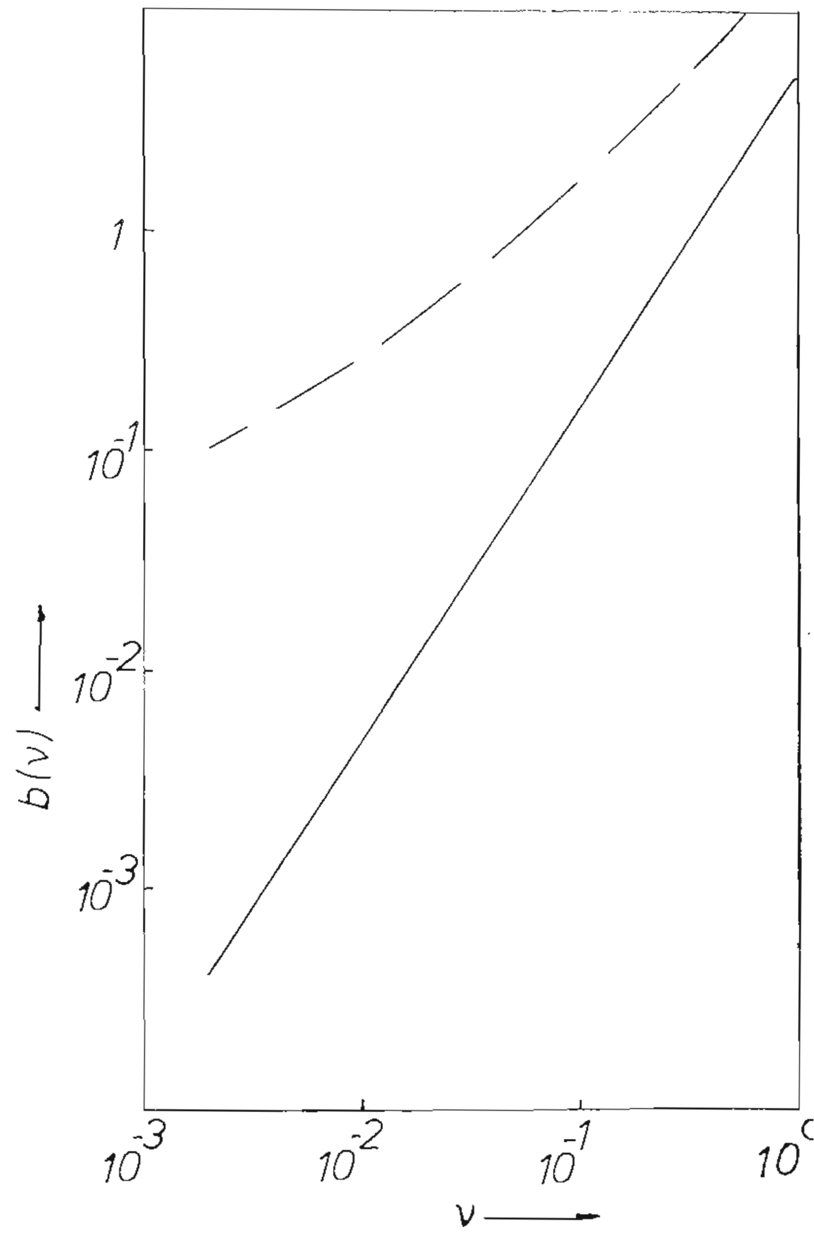

Fig. 3

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

$$N[(\hbar / \sqrt{2mE}) + R_0]^3 >> 1 \text{ or } \nu < (NR_0^3)^{2/3} / [1 - (NR_0^3)^{1/3}]^2 \qquad (19)$$

The comparison of $\alpha(\nu)$ and $\beta(\nu)$ as a functions of the energy in the cases of random and correlated impurity distribution is given in Fig. 2 and Fig. 3.

Now we are going to discnss briefly the influence of the impurity potential on the electronic states near the Fermi level. First of all it is clear that the existence of a band tail leads to a decrease in the Fermi energy. The corresponding correction is $\Delta E_F^{(1)} = -\gamma^2 / 8E_F^{(0)} << E_F^{(0)}$ and can be obtained from the semiclassical density of states (5). Another correction arises from the electron-electron exchange interaction $\Delta E_F^{(2)} = -k_F q^2 / 4\pi^2 \varepsilon\varepsilon_0$ [3].

The scattering of the electrons by the random impurity potential gives the main contribution to the relaxation time. We will recall the

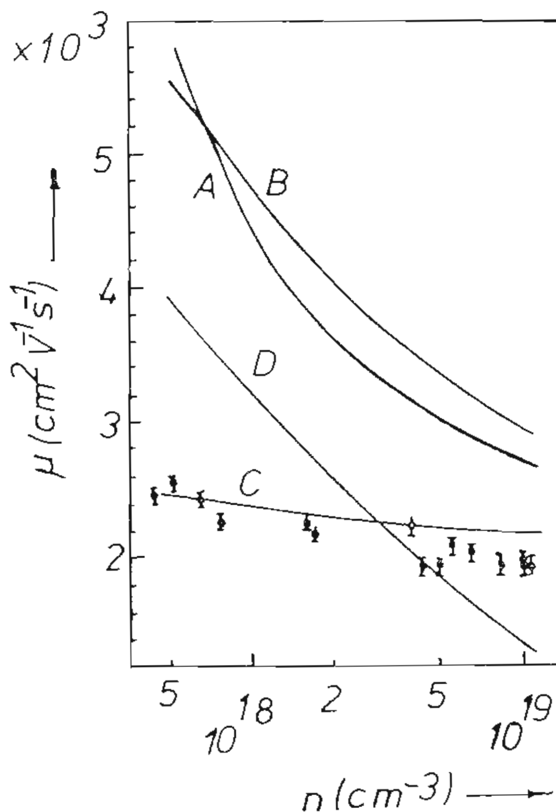

Fig. 4

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

result for the electron mobility in degenerated GaAs [10] which has been reported on our previous symposium (Fig. 4), There we have used the following relaxation time [11]:

$$T^{-1} = \alpha\gamma^2 / \hbar k_F R E_F \qquad (20)$$

Similar calculations have been performed recently for InAs [12]. The situation in this relatively small gap material is different due to the fact that there exist a large number of intrinsic electrons and holes in the high-temperature plasma at the temperature T_0 which is about 800 K. The total screening length R is given by $R^{-2} = R_{ni}^{-2} + R_0^{-2} + R_s^{-2}$ where $R_{ni} = (\varepsilon\varepsilon_0 k_B T_0 / 2n_i q^2)^{1/2}$ is the Dehye radius due to the $n_i(T_0) \approx 10^{18} cm^{-3}$ intrinsic carriers. However at low temperature the latter recombine and partly unscreen the impurity potential. This can destroy the correlation in the impurity distribution provided that $n_i \gg N_D$ [8]. Then results for random distribution should be valid. In the opposite case, $n_i \ll N_D$, the correlation should be essential.

This theoretical conclusions are in agreement with our calculations which are shown in Fig. 5a and Fig. 5b. It is evident that at donor concentrations $N_D \leq 6 \times 10^{17} cm^{-3}$ the better description of the experimental data is given by the curves obtained in the case of random distrihution. At concentrations $N_D > 4 \times 10^{18} cm^{-3}$ the curves for correlated distribution should be used in order to obtain a reasonable compensation ratio, consistent with the radioactivation analysis and luminescence data.

3. ELECTRONIC STATES AND CONDUCTIVITY IN HEAVILY DOPED STRONGLY COMPENSATED SEMICONDUCTORS

Now we shall discuss the energy states in heavily doped semiconductors with a large degree of compensation. It is well-known from the experiment that the strong compensation changes the character of the conductivity from metallic to thermally activated one. This phenomenon has been called Metal-to-non-metal transition, and was discussed first by Mott and Twose [13] some twenty years ago. The reason for this transition is as follows. Introducing acceptors with con centration N_A in a heavily doped semiconductor leads to the decrease in the electron density $n = N_D - N_A$ in the conduction band. Thus, the electron screening hecomes less effective and the amplitude of

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

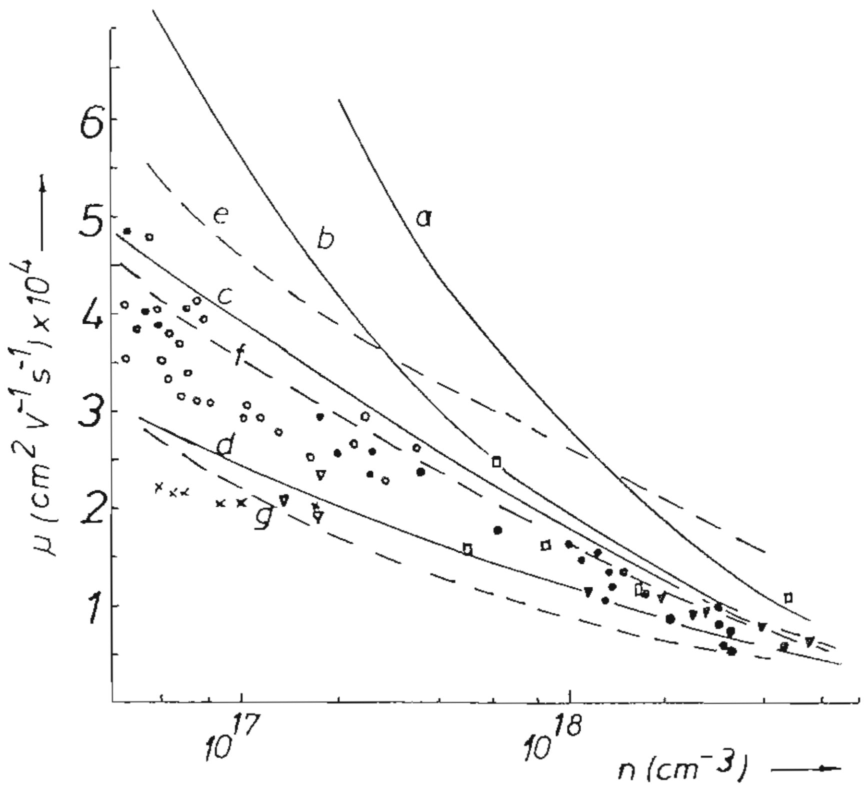

Fig. 5a

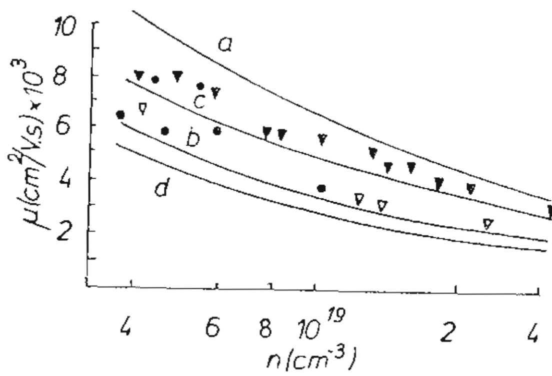

Fig. 5b

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

the random potential is increased. At the same time the Fermi level is lowered so that at some critical degree of compensation it will fall into the region of localised states. Then all the electrons will be captured into the deepest potential wells which are separated from each other by high potential barriers, as shown in Fig. 6.

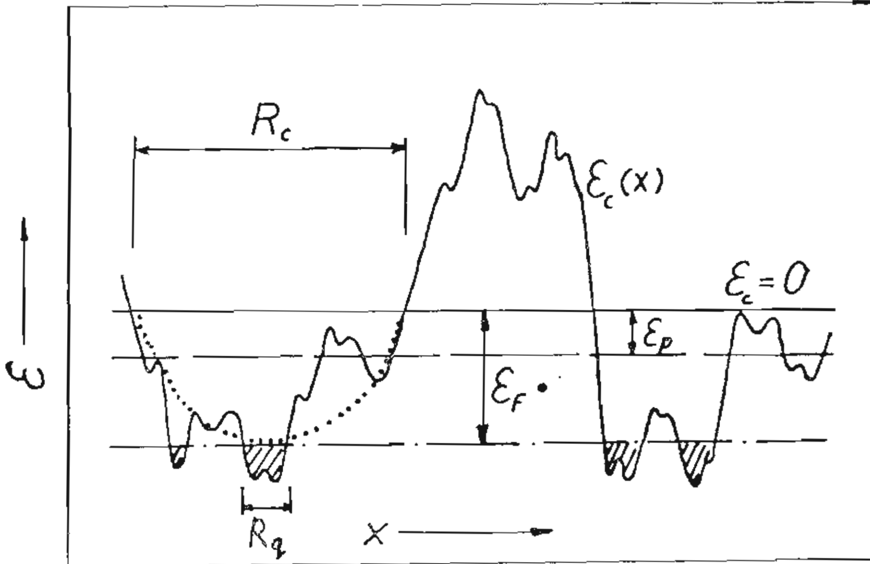

Fig. 6

It is clear that the electron density distribution becomes essentially inhomogeneous in this case, so that the linear screening is no longer valid. Now the screening radius can be determined from the following consideration. The maximum size Rc of the unscreened fluctuations should be found from the neutrality condition which means that the mean electron density $n = (1 - K)N_D$ should be equal to the excess charge in the fluctuation:

$$(N_D R_c^3)^{1/2} R_c^{-3} = (1 - K)N_D \quad \text{or} \quad R_c = N_D^{-1/3}(1 - K)^{-2/3} \tag{21}$$

Here $K = N_A / N_D$ is the compensation ratio.
The fluctuations with size $R < R_c$ cannot be neutralized by the electrons. The characteristic value of the potential fluctuation is

$$\gamma(R_c) \equiv \frac{q^2}{\varepsilon\varepsilon_0 R_c} [N_D(1 + K) R_c^3]^{1/2} \approx \frac{q^2 N_D^{1/3}}{\varepsilon\varepsilon_0 (1 - K)^{1/3}} \tag{22}$$

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

Fluctuations with all sizes smaller than R_c exist aud now the problem for the equilibrium of the electrons in the potential of the short range fluctuations should be solved. Of course, this equilibrium can be achieved only due to quantum effects. One can show that the electrons form metallic drops with typical size of the order $R_q = a_B (N_D a_B^3)^{-1/9}$. This size is defined by the condition that the depth of the typical well $\gamma(R_q)$ should be equal to the Fermi energy of tbe electrons in this well. The fluctuations of size $R < R_q$ create a potential $\gamma(R) < \gamma(R_q)$ and cannot divide the drops into parts (Fig. 5). The electron concentration in the drop is of tbe order of $\tilde{n} = (N_D R_q^3)^{1/2} / R_q^3 = N_D (N_D a_B^3)^{-1/3}$. It is very important that $\tilde{n}$ does not depend on the mean electron concentration n. The typical size of the drop R_q is larger than the mean distance between impurities and $\tilde{n} a_B^3 \gg 1$. Thus, the electrons in tbe drops form a nearly ideal degenerate electron gas.

This qualitative picture has been given by Shklovskii and Efros [14, 15]. It is based on the assumption that the impurities are randomly distributed.

Let us consider the kinetic properties of such a system. The electron drops are isolated from each other by almost non-transparent potential barriers so that d.c. conductivity can be effected only by means of thermal activation or tunneling. The probability for tunneling is very small, hence in a wide range of temperatures the conductivity has an activated character. The activation energy is determined by the minimum energy which an electron should have in order to pass through the whole sample without tunneling. This is impossible if the energy of the electron is equal to the chemical potential, because the drops occupy a small part of the crystal volume. However, this becomes possible if the electron energy exceeds some energy E_p which is called the percolation level [15, 16]. Thus, the activation energy is equal to $E_1 = E_F - E_p$ and is of the order of the characteristic potential fluctuations:

$$E_1 = \nu_1 \gamma(R_c) = \nu_1 \frac{q^2 N_D^{1/3}}{\varepsilon\varepsilon_0 (1 - K)^{1/3}} \qquad (23)$$

where ν_1 is a numerical factor. This formula determines the dependence of the activation energy on the impurity concentration and on the compensation ratio.

It should be noted that the Hall mobility at such conditions be-

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

ιow the pro-
of the short
ilibrium can
that the ele-
er $R_q = a_B$
depth of the
the electrons
ential $\gamma(R) <$
The electron
$R_q^3)^{1/2} / R_q^3 =$
on the mean
larger than
us, the ele-
gas.
i and Efros
e randomly

m. The ele-
transparent
ed only by
y for tun-
es the con-
y is deter-
ve in order
is impos-
potential,
. However,
energy E_p
ion energy
eristic po-

(23)

ependence
d on the

itions be-

comes extremely small and a theory of the Hall effect has not y
constructed. Thus, the experimental determination of the co
tion ratio K is not possible and this hampers the calculation o

At lower temperatures ($kT < E_1$) the conductivity if heavil
compensated semiconductors becomes of hopping type and is
by means of phonon-assisted tunneling of electrons with energ
the Fermi level [16 to 19]. The spatial distribution of the electr
and that of the discrete levels in them determine both the va
the temperature dependence of such hopping conductivity. T
resistivity can be described by the expression

$$\rho \sim \exp[(T_a / T)^a]$$

where α takes successively the values 1, 5/11, 1/4 and 1/2 with l
the temperature. The characteristic temperature T_a depends
concentration and the degree of compensation.

The case $\alpha = 1$ is analogous to the hopping conductivity in
doped semiconductors. In the present case it describes the tu
of electrons through potential barriers of size $R \leq R_c$ for wh
tunneling may become more probable than the activation to t
colation level when the temperature is low enough [16].

In the case $\alpha = 5/11$ the electrons tend to hop between s
remote states with a smaller energy difference, which are cre
fluctuations of various size between $R_q < R < R_c$ [16].

At lower temperatures the well-known Mott's law should l
($\alpha = 1/4$) since the electron hopping is effected on distances la
mpared to R_c [17, 19]. Then one can suppose that the density o
g_F near the Fermi level is nearly constant, which is a necessa
dition for this law to be valid.

At very low temperatures tbis condition may be violat
hopping at such temperatures is realized in a very narrow energ
near the Fermi level, where the density of states changes q
cally with energy and vanishes on the Fermi level. This is the
led Coulomb gap which is due to the electron-electron inte
[18]. In this case the relation (24) with $\alpha = 1/2$ holds.

It has been shown by Shklovskii and Efros [16, 20] that th
of validity of Mott's law at very strong compensation may
extremely low ($\simeq 10^{-3}$K) temperature. This can make its obs
impossible. Moreover, the existence of the Coulomb gap may
similar dependence.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

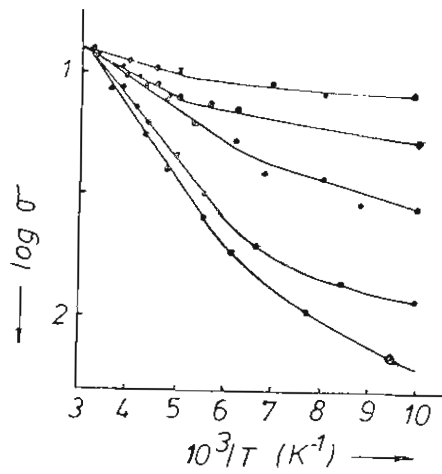

Fig. 7a

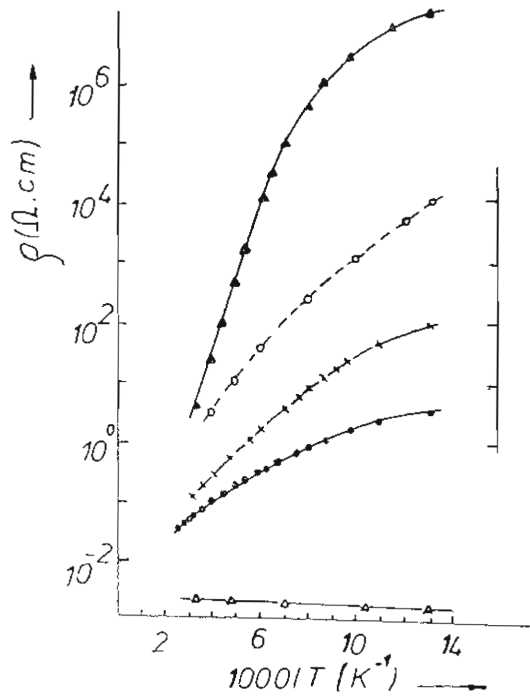

Fig. 7b

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

In the paper [21] some theoretical considerations are given that in the case of correlated impurity distribution the range of validity of Mott's law is shifted towards higher temperatures. This enables its observation in principle.

The characteristic temperatures $T\alpha$ for all cases of hopping conductivity are given in [21] in the case of correlated distribution.

Let us now discuss the experimental data. Thermally activated conductivity in heavily doped compensated GaAs, Ge and CdTe has

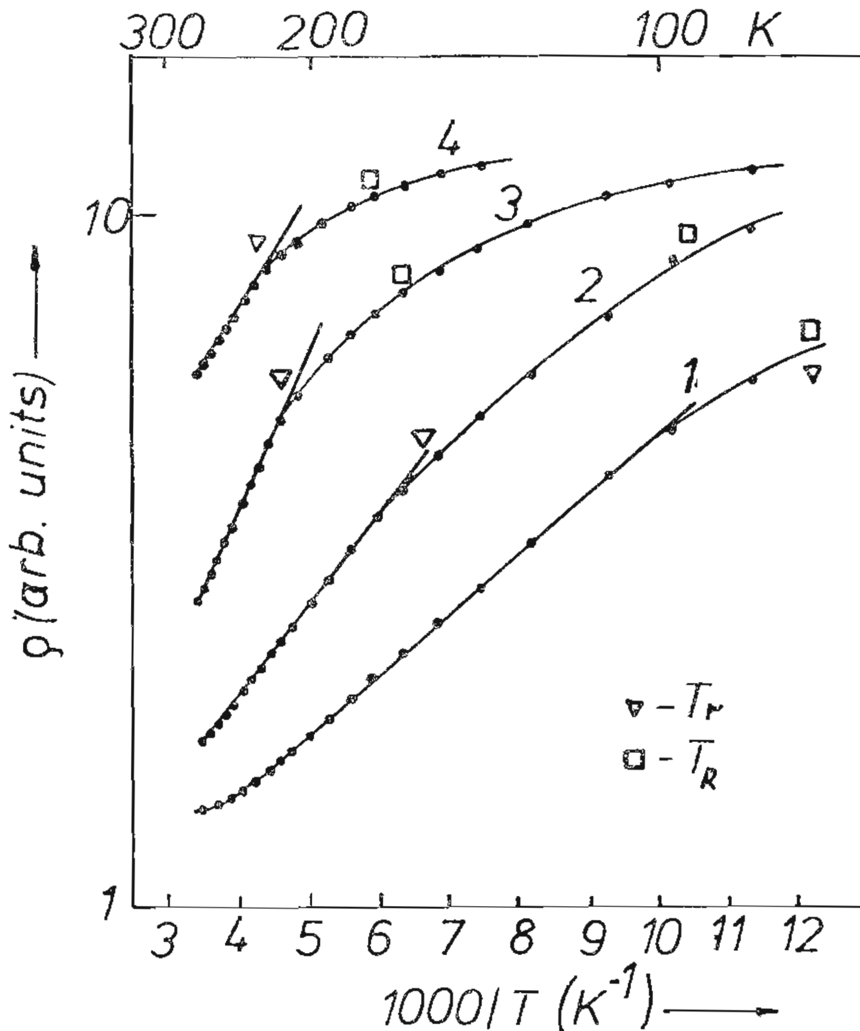

Fig. 8

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

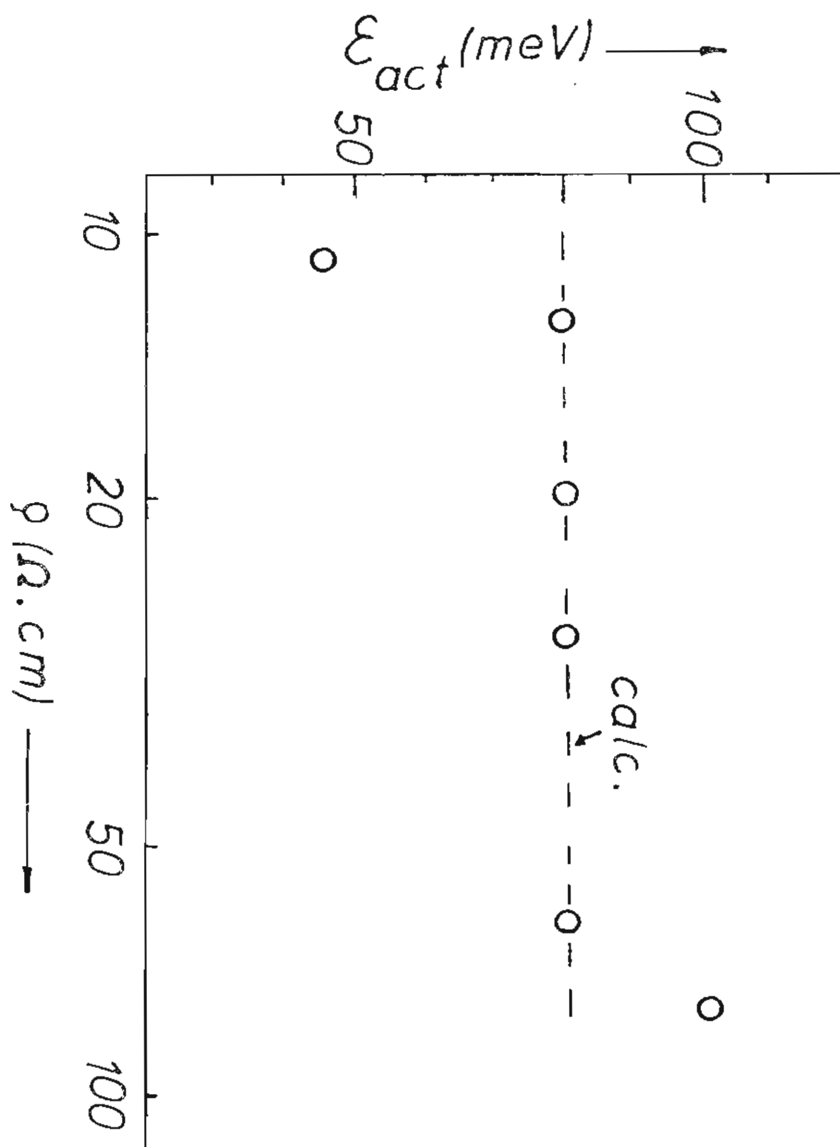

Fig. 9

been investigated in [22 to 24]. The activation range is clearly seen in Fig. 7 where the activation energy is increased with increasing the compensation ratio. The results in Fig. 7 refer to samples with random impurity distribution. The authors have not given a quantitative interpretation of the activation energy values.

In the paper [24] LPE layers of GaAs compensated with Te and Ge presumably with correlated impurity distribution have been instigated. The activated conductivity for 4 p-type samples with majority impurity concentration in the range 5×10^{17} to $1.3 \times 10^{19} cm^{-3}$ is shown in Fig. 8.

The values of the activation energy for several samples with majority impurity concentration $10^{19} cm^{-3}$ and various compensation ratio (resistivity) are given in Fig. 9. It is evident that in a large range the activation energy is constant.

The value of E_{act} can be calculated from (23) by replacing R_c by R_0. As one can see, from (15), R_0 and E_{act} do not depend on the value of the compensation ratio if only $1 - K << 1$. This leads to a good agreement between the experimental and calculated values for E_{act} in the whole concentration range. The best agreement is obtained at concentrations $10^{19} cm^{-3}$, as can be seen in Fig. 9.

The hopping conductivity ranges which replace the activated one have been investigated in a number of papers [21 to 23, 25, 26]. in GaAs, Ge and CdTe. The observed hopping conductivity has been usually interpreted according to Mott's law [22, 23], which has given extremely large values for the density of states at the Fermi level g_F, up to $10^{23} eV^{-1} cm^{-3}$. As predicted by Shklovskii [16] and shown by Redfield [25], the experimental data are better described by the dependence $\rho \sim \exp(T_a / T)^{1/2}$ which is nearly identical to (24) with $\alpha = 5/11$. (Fig. 10-α).

In the paper [22] the hopping conductivity in CdTe samples cut in different directions has been investigated. The regimes $\rho \sim \exp(T^{-1/4})$ or $\rho \sim \exp(T^{-1/2})$ have been observed (Fig. 10b) for various orientation. The authors have assumed that Mott's law has been observed due to the presence of the impurity correlation only in one spatial direction, perpendicular to the equipotential planes, in accordance with some theoretical conclusions, given by Shklovskii [16].

The hopping conductivity in heavily doped compensated LPE GaAs layers with fully correlated impurity distribution has been investigated in [21]. (The results about the activated conductivity in some

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

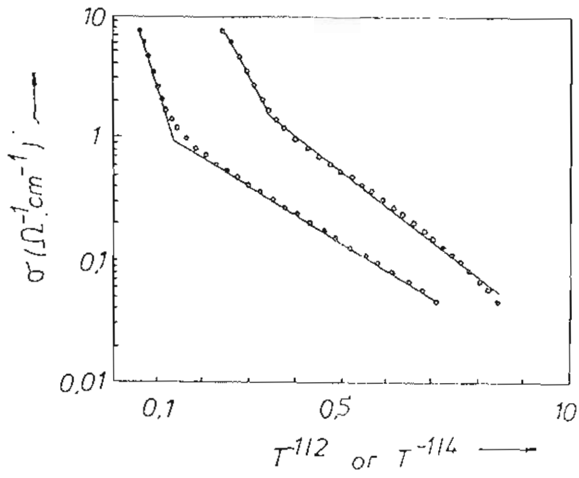

Fig. 10a

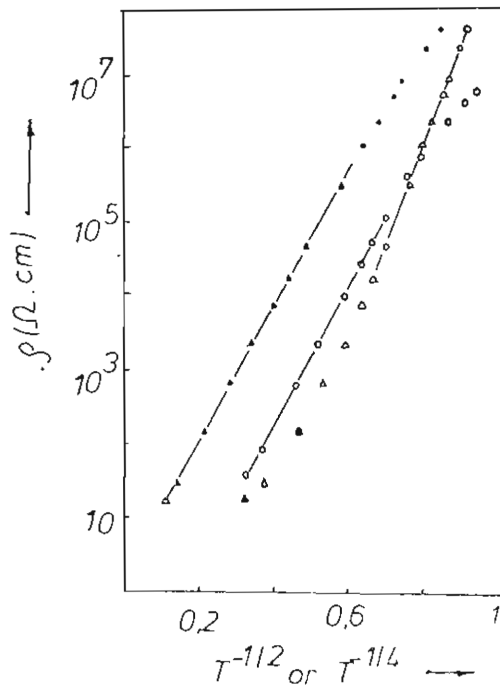

Fig. 10b

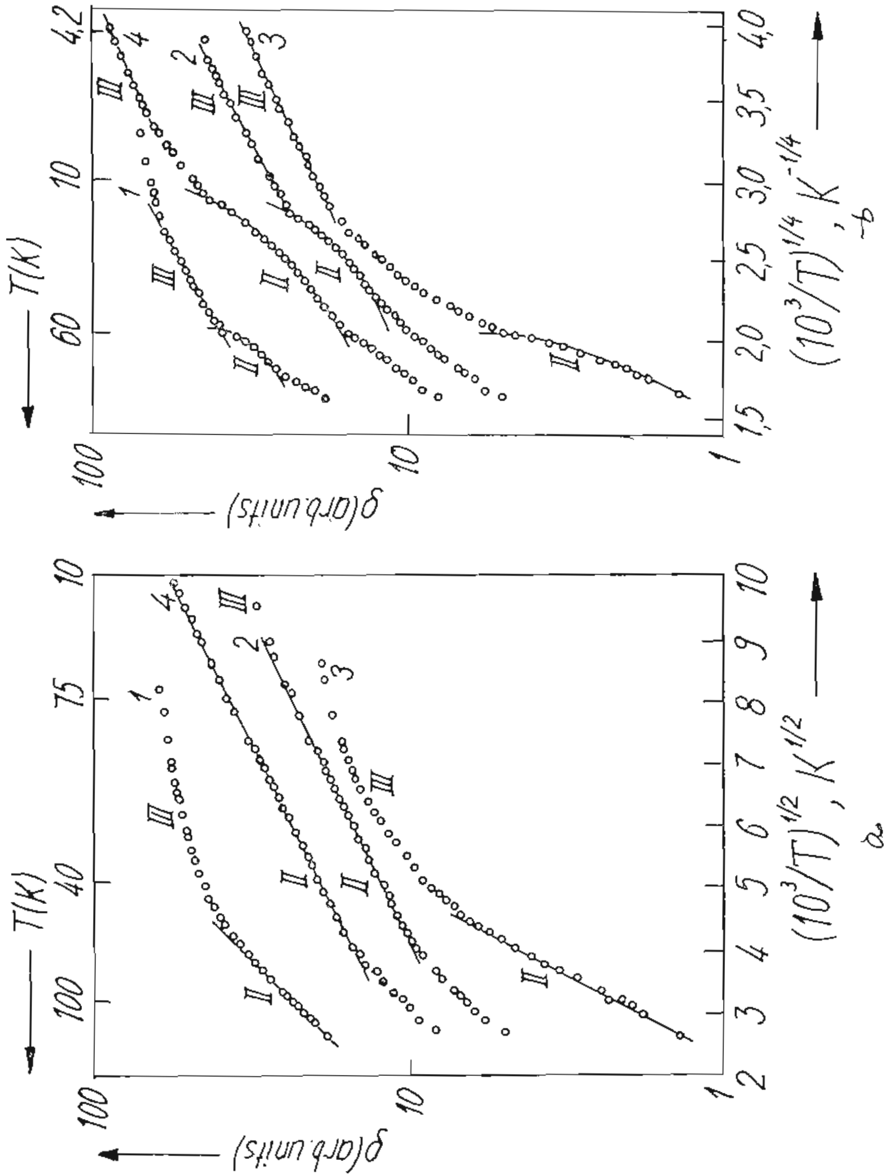

Fig. 11

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

samples have been discussed above — Fig. 8, 9). In n-type samples the theoretically predicted hopping regimes with $\alpha = 1, 5/11 \approx 1/2$ and $1/4$ have been observed. In order to verify this, we present the plot of some experimental data in coordinates $T^{-1/2}$ and $T^{-1/4}$ (Fig. 11) for samples with different impurity concentrations, corresponding to those in Fig. 8. The linear ranges II in coordinates $T^{-1/2}$ show superlinear dependences in coordinates $T^{-1/4}$. In the same time, the sublinear ranges III in coordinates $T^{-1/2}$ become linear in coordinates $T^{-1/4}$. There is an overall agreement between theoretically estimated and experimentally derived parameters in the formula $\rho \sim \exp(T_a / T)^a$, namely T_a and the theoretically predicted ranges of validity of all the three laws. The calculation was based on the theory for correlated distribution, as discussed before.

The experimentally derived values for the density of states at the Fermi level g_F vary between 6×10^{18} and $2 \times 10^{19} eV^{-1} cm^{-3}$ for sample No 1 and 4, respectively, which are in a good agreement with the theoretical estimations. This fact allows to obtain a reliable experimental value for the difference $1 - K$. For the samples No 1 - No 4 this quantity varies between 0.09 to 0.025. The corresponding K values are 0.91-0.975 and agree with other electrical measurements and the growth conditions.

In conclusion, we can say that the theory of heavily doped or / and strongly compensated semiconductors can give a quantitative description of the conductivity provided we take into account the correlation in the impurity distribution.

REFERENCES

1. V. L. Bonch-Bruevich, The Electronic Structure of Heavily Doped Semiconductors, Elsevier, Amsterdam (1966).
2. N. F. Mott, Adv. Phys. 16, 49 (1967).
3. B. I. Shklovskii, Al. Efros. Electronic Properties of Doped Semiconductors, Nauka, Moskow (1979) (in Russian).
4. R. A. Abram, G. J. Rees, B. L. H. Wilson. Adv. Phys. 27, 799 (1978).
5. E. O. Kane. Phys. Rev. **131**, 79 (1963).
6. M. I. Dyakonov, A. L. Efros, D. L. Mitchell. Phys. Rev. **180**, 813 (1969).
7. B. I. Halperin, M. Lax. Phys. Rev. 148, 722 (1966).
8. Yu. S. Galpern, A. L. Efros. Fiz. Tekh. Poluprov., 6, 1081 (1972).
9. Z. G. Koinov, I. Y. Yanchev. J. Phys. C: Sol. St. Phys. **11**, L 253 (1978).
10. I. Y. Yanchev, B. G. Arnaudov, S. K. Evtimova. J. Phys. C: Sol. St. Phys. 12, L 765 (1979).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

11. M. Yussouff, J. Zittartz. Sol. St. Commun. **12**, 959 (1973).
12. I. Y. Yanchev, R. T. Yakimova. Proc. 6th Internat. School on Defects in Crystals, Krynica, Poland (1980), to be published.
13. N. F. Mott, W. D. Twose. Adv. Phys. **10** 107 (1961).
14. B. I. Shklovskii, A. L. Efros. Zh. Eksp. Teor. Fiz. **60**, 867 (1971).
15. B. I. Shklovskii, A. L. Efros. Zh. Eksp. Teor. Fiz. **61**, 816 (1971).
16 B. I. Shklovskii. Fiz. Tekh. Poluprov. **7**, 112 (1973).
17. N. F. Mott. Phil. Mag. **19**, 835 (1969).
18. A. L. Efros, B. I. Shklovskii. J. Phys. C: Sol. St. Phys. **8**, L 49 (1975).
19. V. Ambegaokar, B. I. Halperin, J. S. Langer. Phys. Rev. **B 4**, 2612 (1972).
20. B. I. Shklovskii, A. L. Efros. Uspekhi Fiz. Nauk, 117, 401 (1975).
21. B. G. Arnaudov, D. S. Domanevskii, I. Y. Yanchev. Phys. Stat. Solidi, (b) **91**, 311 (1979).
22. I. V. Agrinskaya, E. D. Krymova. Fiz. Tekh. Poluprov. **6**, 1783 (1972).
23. A. G. Gadjiev, S. M. Ryvkin, I. S. Shlimak. Pisma Zh. Teor. Exper. Fiz., 15, 605 (1972).
24. B. G. Arnaudov, D. S. Domanevskii, S. K. Evtimova. Fiz. Tekh. Poluprov. **11**, 226 (1977).
25. D. Redfield. Adv. Phys. **24**, 21 (1975).
26. A. G. Zabrodskii, A. N. Ionov, V. L. Korchazhkina, I. S. Shlimak. Fiz. Tekh Poluprov. **7**, 1914 (1973).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

ΠΕΡΙΛΗΨΗ

ΜΕΛΕΤΗ ΗΛΕΚΤΡΙΚΩΝ ΙΔΙΟΤΗΤΩΝ ΗΜΙΑΓΩΓΩΝ ΙΣΧΥΡΗΣ ΠΡΟΣΜΕΙΞΕΩΣ

Ὑπὸ

I. Y. YANCHEV ΚΑΙ B. G. ARNAUDOV

(Ἐργαστήριο Φυσικῆς Ἡμιαγωγῶν καὶ Τεχνολογικῶν Ἐρευνῶν Πανεπιστήμιο Σόφιας)

Τὸ τυχαῖο δυναμικὸ ποὺ ὀφείλεται στὴ διακύμανση τῆς συγκεντρώσεως φορτισμένων προσμείξεων στὴ περίπτωση ἰσχυρῆς προσμείξεως διαμορφώνει τὴν ἐνεργειακὴ ταινία τοῦ ἡμιαγωγοῦ. Τὰ θεωρητικὰ ἀποτελέσματα γιὰ τὰ στατιστικὰ χαρακτηριστικὰ αὐτοῦ τοῦ τυχαίου δυναμικοῦ ὅπως ἐπίσης καὶ ἡ συνάρτηση πυκνότητας τῶν καταστάσεων δίνονται σὲ χαμηλὴ καὶ ἰσχυρὴ ἀντιστάθμιση.

Γιὰ ἰσχυρὴ ἀντιστάθμιση καὶ ἀρκετὰ χαμηλὲς θερμοκρασίες τὰ πλάτη τοῦ δυναμικοῦ εἶναι μεγάλα καὶ τὰ ἠλεκτρόνια ἐντοπίζονται στὶς βαθύτερες διακυμάνσεις τοῦ δυναμικοῦ. Τότε ἡ ἀγωγιμότητα ἐπηρεάζεται ἀπὸ τὴ θερμικὴ ἐνεργοποίηση τῆς ἀκμῆς εὐκινησίας ἢ ἀπὸ ἅλματα μεταξὺ ἐντοπισμένων καταστάσεων. Διάφορες περιπτώσεις ἀγωγιμότητας ἀπὸ ἅλματα στὶς ἐντοπισμένες καταστάσεις μὲ μία ἐξάρτηση τοῦ τύπου $\sigma \sim \exp(-T^{p})$ καὶ $p = 1$, 5/11, 1/4 ἢ 1/2 ἔχουν προβλεφθεῖ θεωρητικὰ καὶ ἔχουν διαπιστωθεῖ πειραματικὰ στὸ GaAs, CdTe, Ge κ.λ.π.

Λαμβάνοντας ὑπόψη τὸν συσχετισμὸ στὴ κατανομὴ τῶν προσμείξεων μποροῦμε νὰ διερευνήσουμε τὴν σχέση μεταξὺ θεωρητικῶν καὶ πειραματικῶν τιμῶν τῶν κυριότερων παραμέτρων στὴν ἀγωγιμότητα τοῦ GaAs. Ἡ σκέδαση ἠλεκτρονίων ποὺ ὀφείλεται στὸ τυχαῖο δυναμικὸ προσμείξεων GaAs καὶ InAs συζητιέται ἐπίσης περιληπτικά.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.